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SAFEGUARDS FOR FINAL DISPOSAL OF SPENT NUCLEAR FUEL

Methods and technologies for the Olkiluoto site

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Preface

The final disposal of the nuclear material shall introduce new safeguards concerns which have not been addressed previously in IAEA safeguards approaches for spent fuel. The encapsulation plant to be built at the site will be the final opportunity for verification of spent fuel assemblies prior to their transfer to the geological repository. Moreover, additional safety and safeguards measures are considered for the underground repository. Integrated safeguards verification systems will also concentrate on environmental monitoring to observe unannounced activities related to possible diversion schemes at the repository site.

The final disposal of spent nuclear fuel in geological formation will begin in Finland within 10 years. After the geological site investigations and according to legal decision made in 2001, the final repository of the spent nuclear fuel shall be located at the Olkiluoto site in Eurajoki. The next phase of site investigations contains the construction of an underground facility, called ONKALO, for rock characterisation purposes. The excavation of the ONKALO is scheduled to start in 2004. Later on, the ONKALO may form a part of the final repository.

The plans to construct the underground facility for nuclear material signify that the first safeguards measures, e.g. baseline mapping of the site area, need to take prior to the excavation phase. In order to support the development and implementation of the regulatory control of the final disposal programme, STUK established an independent expert group, LOSKA. The group should support the STUK in the development of the technical safeguards requirements, in the implementation of the safeguards and in the evaluation of the plans of the facility operator. This publication includes four background reports produced by this group. The first of these “NDA verification of spent fuel, monitoring of disposal canisters, interaction of the safeguards and safety issues in the final disposal” describes the new safeguards concerns for spent nuclear fuel. The three others “Use of satellite and airborne remote sensing in the safeguards of a nuclear waste repository”, “Environmental sampling in monitoring spent fuel repository” and “Seismic monitoring of rock excavations, baseline at Olkiluoto nuclear waste repository site” propose new safeguards approaches to be applied at the Olkiluoto repository site.

NDA VERIFICATION OF SPENT FUEL, MONITORING OF DISPOSAL CANISTERS, INTERACTION OF SAFEGUARDS AND SAFETY ISSUES IN THE FINAL DISPOSAL

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Abstract

The report reviews into technologies available for the NDA verification of the spent fuel assemblies and canisters applicable in the disposal of spent fuel. Needs for technological development are identified. The monitoring needs, and available and prospective technologies are discussed, taking into account of possibility to use process performance assessment and quality assurance data as well as radiation safety monitoring data also for safeguards purposes. Some aspects of the safeguards and safety interaction are briefly discussed.

Contents

1 Introduction

After the decision made in 2001 to site the final repository of the spent nuclear fuel at the Olkiluoto site in Eurajoki the final disposal programme in Finland has become site-specific. The next phase contains building of an underground facility, called ONKALO, for rock characterisation and site confirmation studies. If found suitable, ONKALO may form a part of the final repository. The construction of ONKALO is scheduled to start in 2004. [1] This signifies that the first safeguards measures, e.g. base level mapping of the site area, need to take place as early as 2003. Safeguards requirements need to be specified on the level influencing the facility design for proceeding with designing of the final disposal facility and for starting of the pre-operational phase by constructing the ONKALO facility. [2]

To support the development and implementation of the regulatory control of the final disposal programme, STUK has established an independent expert group, LOSKA, in April 2002. The group should support the STUK in the development of the technical safeguards requirements, in the implementation of the safeguards and in the evaluation of the plans of the facility operator. Additionally the group may assist the STUK in defining R&D needs related to the safeguards of the final disposal.

The target of the NDA or monitoring in this report is the spent fuel itself. Therefore this report deals with the operational phase only, as spent fuel is handled only during this phase in the final disposal facility. On the other hand, the report considers the whole process of the final disposal starting from the interim storage through the encapsulation plant down to the underground final repository.

This report reviews into the present status of the NDA technology, which may be useful in the verification measures of the spent fuel subject to final disposal. Also the monitoring technology applicable to the final disposal facility is reviewed. Furthermore, it briefly discusses the safety aspects of the safeguards measures during the final disposal. The needs for technological R&D on these disciplines will be identified and discussed. The safeguards approach of a model repository as drafted in the report of the SAGOR task is used as a reference. [3]

2 NDA applicable for verification of spent fuel assemblies

2.1 Needs and available techniques for NDA

There are two kinds of needs for verification measurements of spent fuel assemblies subjected to final disposal:

1. It must be verified that the residual heat generation rate does not exceed the accepted level;
2. It must be verified that the nuclear material content of the spent fuel is as declared.

Temperature is an important parameter influencing on the performance of the bentonite buffer material around the spent fuel canister in its disposal location. Therefore it is of utmost importance to limit the surface temperature of the canister. The surface temperature depends on the heat generation rate of the residual activity of the fuel assemblies and on the thermal conductivity of the near-field environment of the canister. [4] As the total heat generation of each disposal canister is limited, one must make sure that the residual heat generation of each assembly is known with sufficient reliability. The residual power can be verified e.g. by measuring the gamma emission rate or the activity of ^{137}Cs. These NDA verification measurements can be automated and performed quite rapidly. The radiometric measurements should be calibrated calorimetrically for a set of reference assemblies. [5]

There are no specific IAEA safeguards criteria yet available for the spent fuel subject to final disposal. The closest analogue having the safeguards criteria is the spent fuel designated for difficult-to-access. According to the IAEA safeguards criteria [6], the fuel prior to its becoming difficult-to-access must be subjected to item counting, item identification and NDA that provides a high detection probability for gross and partial defects. For the fuel designated for final disposal the verification should fulfil at least those requirements set forth for the fuel designated for difficult-to-access.

The Finnish national safeguards requirements for the final disposal cannot be less stringent than the IAEA and Euratom requirements. Discussion has been started on the requirement of a partial defect level verification of each fuel item designated for final disposal. In some contexts the requirement of a pin-level verification has been mentioned for those fuel items, whose design enables dismantling in the NPP. [7]

Spent fuel measurement systems able to measure the neutron and gross gamma emission profiles are commercially available. [8]

Technology capable for pin-level verification, based on gamma emission tomography, is under active development and some major breakthroughs have been achieved. It has been shown, both by simulation and experimentally, that a BWR fuel assembly can be verified at the pin level. [9, 10] This should apply also to a VVER-440 assembly, which has comparable cross sectional dimensions, although experimental evidence on that is missing so far. For a PWR assembly with a larger cross section, in order to achieve a pin level verification in all cases, still some improvement is needed. [11]

2.2 Research and development needs

Should the requirement for pin-level verification be adopted, the technique and equipment available would not yet be mature for direct application of the gamma emission tomography. Gamma emission tomography systems applicable for verification of spent fuel are not yet commercially available. The following technological development needs can be identified: [11]

1. improvement of the signal quality;
2. better mechanical accuracy;

3. development of signal analysis to distinguish fuel assemblies of "advanced technology" like those containing rods of partial-length and rods with burnable absorber;
4. automation in the interpretation of the measurement results.

The high signal quality is fundamental. The detector detects four different kinds of gamma quanta as depicted schematically in Figure 1. Only the quanta of type 1 in Figure 1 contribute to the signal. The parasitic contributions can be reduced by different improvements. The crosstalk through the collimator, quanta of type 2 in Figure 1, cannot be eliminated by energy-dispersive counting systems (low-level discrimination or multi-channel pulse-height analysis). In a multidetector system the collimator thickness is limited by the distance between the detectors. Type 3 and 4 quanta can be best discriminated by pulse-height analysis. This requires a detector with high full-peak efficiency and high resolution. A perfect detector fulfilling all requirements has not yet been found, and the best detectors so far tested are far from perfect.

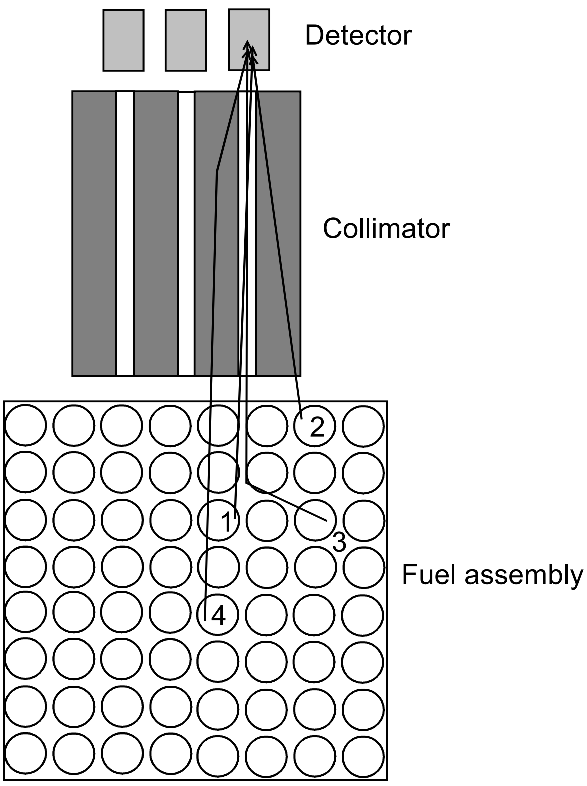

Figure 1. Main types of gamma rays seen by the detector in gamma emission tomography. See text for explanation.

One prototype gamma emission tomography device capable for fast data collection has been built and demonstrated. [12] This prototype was optimised for high-efficiency data collection of the high-energy gamma radiation from ^{140}Ba/La. This nuclide can be used for the non-destructive determination of the power distribution during the irradiation period preceding the evacuation of the assembly. The prototype device demonstrated that it should be possible to implement a gamma emission tomography device capable for mapping of the fuel assembly cross section in 20 minutes on one axial level.

The mechanical precision so far achieved in the prototype devices requires further improvement. The most difficult problem is to define the position of the fuel assembly relative to the detector/collimator system accurately enough. It should be able to take into account possible deformations of the fuel assemblies during irradiation. A laser-optical measurement system could possibly be able to measure the actual position of the fuel assembly with sufficient precision.

If the technical problems described above can be solved, the signal quality could provide good opportunities for a reliable unfolding of the measured data to produce a map of fuel pins. The next step would be the development of an automatic system for evaluation of the resulted map and for comparison with the operator's data. This system should be matched with the requirements of the disposal process allowing its smooth integration into the process. A demand of high detection probability of all irregularities and very low or zero probability of false alarms should be fulfilled.

3 NDA applicable for verification of disposal canisters

3.1 Available techniques

If an unbreakable continuity of knowledge can be achieved by multiple independent C/S and by collection into a data bank of all process control data of the encapsulation and disposal process, there should be no need for verification of the nuclear material content of a closed and sealed disposal canister.

However, a provision should be made, should any need arise, to verify that all fuel assemblies are present in a closed disposal canister, as declared. The following techniques might be applicable:

1. measurement of the gross weight of the canister;
2. verification of the presence of the number of highly radioactive items corresponding to the number of fuel assemblies declared;
3. to measure a radiation signal corresponding to the expected yield of the fuel assemblies in the canister.

In the first case a load cell could be used for verifying the total mass of the sealed disposal canister. The accuracy of the mass measurement should be well below half of the weight of one fuel assembly, i.e. below 100 kg. In order to reach this goal the tare of individual empty canisters should be equal within tens of kilograms. If the variation of the canister masses exceeds this limit the tare of each canister should be measured before inserting the assemblies.

The second measurement would give an independent verification of the presence of the number of fuel assemblies as declared. The only conceivable measurement method, which could be able to verify the presence of all twelve assemblies, would be a collimated gamma-ray measurement above the top of the lid of the canister. An SFAT-like device could scan over all assembly positions to detect the number and position of the radiation maxima corresponding to the declared loading pattern of the canister. It is highly improbable that any specific attribute, e.g. the photo peak of ^{137}Cs, could be detectable through the heavy lid structures of the canister.

In the third technique the measurement of either gamma or neutron radiation through the sidewall of the canister could be considered. The problem of radiation measurement around side of a canister or cask has been studied recently under MSSP Tasks to the IAEA safeguards. [13] It was concluded that in a removal scenario the change of the gamma radiation level was so small that even a peripheral assembly could be removed without being detected. A replacement could be used to compensate for the weight change. The replacement of the outer assemblies with dummies would certainly be detected, but the central assemblies could be replaced without being detected due to their small contribution to the gamma signal.

Recently measurement of passive neutron emission distribution of CASTOR casks has been attempted for verification of the presence of the declared number of fuel assemblies. [13] Promising results have been achieved. It could be assumed that the weaker shielding and the lower amount of fuel assemblies in the final disposal canister as compared to the CASTOR cask should have a favourable influence to this kind of measurement. If the neutron emission of individual fuel assemblies could be reliably correlated with the azimuthal neutron flux distribution of a loaded canister, this method could be developed for verification of the contents of a sealed canister.

This would make it important to measure the total neutron emission of each assembly before inserting into the canister. This measurement could be easily integrated in the assembly verification measurement system considered in Section 2. The capability of neutron distribution measurement as a verification method for the disposal canister should deserve further study.

3.2 Research and development needs

Should a verification option of a sealed disposal canister be considered necessary, the feasibility of those radiation-based NDA verification approaches considered in Section 3.1 should be studied, and a method and a device based on that method should be developed and established before starting the encapsulation and disposal activities.

4 Monitoring of encapsulation and disposal process

A due control of the encapsulation and disposal process would require comprehensive monitoring and data collection of all material streams involved. This data would serve the performance confirmation and quality assurance. A properly designed and implemented monitoring system could simultaneously serve the collection of data for safeguards purposes. The monitoring activities in the point of view of safety and performance confirmation of the disposal as well as in the point of view of safeguards have been considered in various consultants meetings and advisory group meetings of the IAEA. [14, 15] The interaction between safety and safeguards measures, especially monitoring, was first dealt with in September 2002 in an expert group meeting in Oskarshamn Sweden. [15]

One can distinguish three different kinds of material streams in the encapsulation and disposal process:

1. the main stream of the spent fuel;
2. complementary material streams;
3. back streams.

4.1 Main stream of spent fuel

Spent fuel should be present only in the main stream. In the encapsulation plant and in the repository this stream comprises the following activities:

1. receipt of a full transport cask;
2. verification of the integrity of the cask and the seals;
3. temporary storage of transport casks;
4. transfer of the cask into hot cell;
5. removal of seals and opening the lid;
6. transfer of the fuel assemblies from the cask into the disposal canister;
7. closing and sealing the disposal canister;
8. temporary storage of the canisters ready for disposal;
9. transfer of the disposal canister into the repository;
10. transfer of the canister to its disposal location in the repository;
11. emplacement of the canister into the disposal hole; and
12. filling the disposal hole with bentonite blocks.

According to the present plans the disposal hole will be filled with bentonite blocks almost immediately after the emplacement of the canister. The bentonite layer above the canisters will be about 2 metres. This signifies that after the emplacement all monitoring activities based on the radiation emitted by the canisters are impossible.

In the main stream there should be gates able to record automatically the passing of the cask or disposal canister through the gate. The following parameters should be registered when applicable:

- ID number of the item,
- seals,
- radiation,
- mass of the item.

The technology for monitoring and recording these parameters is readily available.

4.2 Complementary material streams

The following complementary material streams in the disposal process can be identified:

1. receipt of empty disposal canisters and their transfer into the hot cell;
2. fabrication of the bentonite filling blocks and the lids of the disposal holes and their transfer into the repository;
3. empty waste drums for the radioactive waste produced in the process;
4. spare parts and materials needed for repair and maintenance of the equipment and systems.

It is theoretically conceivable that radioactive material could be used to conceal a diversion of spent fuel. Therefore it must be ensured that no radioactive material can be smuggled into the encapsulation facility or repository along with these non-radioactive material streams. This calls for recordable radiation monitoring of all material batches at their entry points.

4.3 Back streams

The material streams out of the encapsulation and disposal plants are here called back streams. They are:

1. empty disposal casks sent back to the interim storage; and
2. waste packages, either radioactive or inactive, brought out of the controlled area.

The empty disposal casks should be visually inspected before closing the lid. Additionally, before departing the facility they should be weighed and inspected for radiation.

The waste packages should be monitored for gamma radiation. An additional neutron measurement using passive and/or active interrogation should ensure that no fissile material is transported out of the facility among the waste.

The technology for monitoring the complementary material streams and back streams of the disposal process is readily available.

5 Monitoring of access points to repository

Special attention should be paid on ensuring that the access points to the repository are well in control. All traffic between the ground level and the underground repository must take place through these strategic points. In this section reference is made to the model repository as described in Ref. [3]. The plans of the Finnish disposal facility, as described in Ref. [16], are based on this the model repository concept.

The access points to the repository can be subdivided into three groups:

1. access points with no traffic;
2. access points with traffic of construction activities and
3. access points with traffic of disposal activities.

In the model repository these three different kinds of access points are physically separated.

5.1 Technical shafts

The technical shafts intended for providing electricity and water supplies and ventilation represent the first kind of access points. Normally they are closed and locked preventing the entrance of man or material through this route. Human presence is necessary only for maintenance and repair purposes. These actions should be recorded in the surveillance data bank. Radiation monitoring and motion sensors can be used. The motion sensors may be used to trigger recording surveillance video cameras covering the area. All events, e.g. unusual radiation levels or triggering of a motion sensor should be recorded. These data should be compared with the records of the declared maintenance and repair activities.

5.2 Entry point of construction activity

During the operational phase of the repository there will be concurrently construction and disposal activities going on. In the model repository described in Ref. [3] the entrances for these two activities are on the opposite ends of the disposal facility. A system of main tunnels connecting these ends is excavated between these two ends. The disposal activity starts from the end of the disposal shaft. Concurrently new disposal vaults are excavated along one main tunnel and this activity proceeds towards the construction shaft. The disposal activity proceeds behind the construction as new disposal vaults are completed. The construction activity and disposal activity are separated by a wall, which is transferred along with the progress of the work. In this concept no radioactive material should be transferred through the construction entry point. The entry point should be equipped with a radiation measurement gate able to monitor the vehicles entering or exiting the repository. This kind of technology is routinely in use for radioactivity and nuclear material control at the frontier crossing points and at the seaports.

For supporting activity to the design information verification it could be useful to automatically measure and record the masses of the vehicles crossing the entry point. This data could be used to keep record of the total rock mass excavated and transported out of the facility.

5.3 Canister shaft and disposal activity

The systems and functions described in this section cover the monitoring of items 9–12 in the list of activities belonging to the main stream of the spent fuel in Section 4.1.

At the upper station of the canister shaft there should be a gate as described in 4.1 recording automatically the ID number, the seals and the mass of the canister, and the radiation level emitted. Neutron-measurement systems should also be considered in this gate.

The second gate could be installed close to the lower station of the canister shaft at the entrance of the tunnel system. The canister transport vehicle could be measured when entering the tunnel and when returning after emplacement of the canister. The mass difference and the difference in the radiation level as measured by the gate could give further confidence that the canister has been transferred in the repository. These checkpoints could also be used to ensure that no radioactive material is transferred out of the repository through this route.

The bentonite block transfers down to the repository should also be registered by the control gates. In this case the registration of the radiation level would add to the confidence that no radioactive items are transferred mixed with the bentonite blocks.

Both these checkpoints should be equipped with recording surveillance video systems to ensure that no tampering of these measurement gates is attempted.

Should there be a need for recording the emplacement of the canister into the emplacement hole, the monitoring instruments for this purpose could be installed in the canister transport vehicle. The data gained during the emplacement could be transferred from the records residing in the transport vehicle into the safeguards data bank as the vehicle has returned from the emplacement trip. Correspondingly the filling of the emplacement hole with bentonite blocks after emplacement of the disposal canister could be recorded using the monitoring instruments installed in the bentonite transport vehicle.

The technology required to implement monitoring of the access points to the repository as well as recording the material passing through the control gate is readily available.

6 Safeguards-safety interaction

6.1 Intrusive instrumentation

Nuclear material control and safeguards measures that compromise safety cannot be accepted. An important principle of the final disposal is that it shall isolate the spent fuel from the biosphere for as long as the material disposed of is considered as being dangerous to the biosphere. This isolation cannot be compromised by any intrusive safeguards measure. This requirement excludes the placement of any instrumentation in the emplacement hole or emplacement vault before backfilling.

6.2 Dual use of safety monitoring instrumentation and NDA

The monitoring used for the radiological surveillance of the rooms of the radiation controlled zone can, and should, be used also for tracking of the route of the spent fuel in the encapsulation plant and in the repository. All significant changes of radiation levels should be attributed to certain cask/fuel/canister transfers. Therefore these events should be automatically recorded together with their time stamps.

The safeguards use of monitoring instrumentation may require authentication of the primary signal. The problem of signal authentication in dual-use systems shall be solved reliably in such cases. The same applies to the dual-use NDA measurement systems. Especially the problem of the maintenance and repair of the dual use instrumentation must be arranged so that it does not hamper the normal disposal process, but yet the authenticity of the signals is guaranteed to the satisfaction of the safeguards authorities.

7 Summary

It is highly probable that the requirement of partial defect verification of each fuel item subject to final disposal will be assumed. The target level of partial defect, which will be required, will depend on the future progress of the NDA verification technology. The authorities may assume a target level, e.g. single pin level of verification, which cannot be met at the moment but which seems to be achievable with a reasonable technological development effort. At the moment the high-energy gamma emission tomography seems most promising method for this verification target.

Simultaneously with the tomography, a gamma spectrometric scanning could be applied to ensure the fulfilment of the residual power generation limit of each assembly. The neutron emission measurement of each assembly may serve in facilitating the verification of a sealed disposal canister if seen necessary. This method needs additional development efforts before it can be considered as operational.

The technologies needed to implement a comprehensive monitoring programme are readily available. This monitoring programme should be accomplished in such a way that it could simultaneously serve both the safety/process control/quality assurance and the safeguards functions.

Integrated unattended systems containing monitoring and NDA functions have been implemented both for the IAEA and for the Euratom safeguards. [17, 18] They are based on modular design letting relatively easy implementation of facility-specific systems. Remote transmission of the data and system diagnostic information from the facility to the safeguards headquarters (IAEA or Euratom) has also been implemented successfully.

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USE OF SATELLITE AND AIRBORNE REMOTE SENSING IN THE SAFEGUARDS OF A NUCLEAR WASTE REPOSITORY SITE

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Abstract

The potential of space-borne earth observation techniques to monitor possible undeclared activities on a nuclear waste repository site was surveyed. The highest potential of earth observation is in the detection of undeclared construction of buildings and roads as well as detection of undeclared quarrying. Real-time applications such as continuous traffic monitoring are not feasible in earth observation applications that require high spatial accuracy. The monitoring system consists of baseline data acquisition that should be done before excavation activities start, of routine monitoring, and of an optional alarm survey. Space-borne synthetic aperture radar (SAR) is suggested as the principal instrument to collect the monitoring data because of its all-weather capability.

Contents

1 Requirements to the safeguards

Earth observation techniques are one tool to prevent illegal use of nuclear waste that has been stored or is being stored in a final repository. This survey discusses benefits and limitations of spaceborne and airborne remote sensing in the monitoring of a final disposal facility site. Also, an outline of a monitoring system is presented and its costs are roughly estimated. A special focus is on the Olkiluoto site, which will be the final disposal site for the spent nuclear fuel in Finland. The report does not discuss how earth observation can be used to locate nuclear plants or how their operation purpose and operative status are defined. The publications that deal with earth observation and safeguards usually discuss just those topics and are not fully relevant to this survey (Potential Applications of Commercial… 1999, Andersson 2000, Jasani et al. 2000).

A final disposal facility is controlled by the IAEA (The International Atomic Energy Agency), as well as by the facility operators, site owners, and by the national authorities. It shall be overseen that the local actors do not commit any unannounced or illegal activities and that the repository site is maintained according to the internationally agreed standards. Since the period of decay of plutonium, the raw material of nuclear weapons is 24 400 years the spent fuel is principally usable for illegal purposes indefinitely. Therefore the repository site should also be monitored continuously over an indefinite time period.

A final disposal facility could be subject to short-term criminal actions when the repository is being filled. After closure the site monitoring should continue to avoid stealing of the spent fuel through tunnels that may have been illegally quarried. It has to be taken into consideration how long it takes to commit a certain type criminal activity when the monitoring methods using earth observation are planned.

Since spent fuel is highly radioactive its transportation requires specific transportation equipment to protect the driver and other transportation personnel. Even though one nuclear fuel assembly weights only 200 to 300 kilograms the total weight of the canister, transportation cask, and the vehicle itself is in the magnitude class of 100 tons. *Removal of a whole fuel assembly from the cask* during the period when the repository is being filled is technically rather straightforward but should be easy to detect with conventional safeguards procedures except in the case when all local actors are involved in the criminal activities (Moran, B. W. and Meer van der, K. 1997). Because of the high radioactivity of the fuel, which makes its transportation difficult it is most likely that the removed fuel would be processed close to the power plant or the repository facilities. However, long distance transportation should also be taken into consideration particularly when the power plant is by the sea.

It is also possible that not the whole assembly but *individual fuel pins are stolen from the assemblies* and replaced by dummy material. This alternative is technically more difficult to accomplish but harder to detect.

Removal of spent fuel from the closed repository through tunneling would certainly require long time period and heavy equipment. Present TBM (Tunnel Boring Method) techniques can make during the day some 20 meters of tunnel large enough for a truck if the rock type is soft. With Finnish rocks the speed is much lower. The shortest possible time to make a tunnel of 500 meters would thus be two to three weeks. In practice the quarrying would be likely done relatively slowly and the tunneling would be started from a distance to the repository to keep it better secret. Moreover, the total length of a sloping access tunnel might be of the order of 5–10 km. The

Table I. Scenarios to remove spent fuel from the declared processing chain, relevant subjects to be monitored using earth observation and required observation frequency.

Scenario	What should be monitored	Longest safe observation frequency	Potential of earth observation*
Stealing of fuel assembly from the cask, refinery on site	Undeclared buildings, traffic, roads	1 month	5
Stealing of fuel assembly from the cask, transportation from the site	Traffic, undeclared roads	1 day (in practice after alarm)	4
Stealing of fuel pins from assemblies (use on site or transportation from site)	Undeclared buildings, traffic, undeclared roads	1 day (in practice after alarm)	3
Quarrying a tunnel to steal fuel from the repository (post closure)	Quarrying sites in the surroundings of the repository, undeclared roads, land and sea traffic	1 month	5

* From highest to lowest: 5…1 (0 would be non-existing)

tunnel quarrying could already be started when the excavation activities for the official repository tunnels are ongoing because this could make diversion easier. The area to be monitored should be relatively large when quarrying activities are concerned.

Table I shows that earth observation has a particularly high potential to detect undeclared activities that require construction of buildings, roads and tunnels. Even though it is impossible to penetrate inside the ground using common remote sensing techniques appearance of a tunnel opening can be detected and particularly accumulation of the quarry waste could be monitored. A reasonably low observation frequency (*i.e.* approximately one month) should be adequate.

The potential to detect undeclared activities is somewhat lower when the fuel is stolen during the filling period of the repository and transported from the site. The lower potential comes particularly from the high requirement to the time frequency for the observations and from the high requirement to the spatial resolution. Daily or even more frequent observations using airborne or space-borne techniques would be very costly to accomplish. After the alarm on possible undeclared activities from other sources earth observation can be utilized to obtain information on them.

2 Earth observation based monitoring system

2.1 Baseline

The proposed monitoring system of the disposal facilities at the repository site has three principal elements: 1) Baseline, 2) Routine monitoring, and 3) Alarm survey (Figure 1).

The baseline survey should be done before starting the excavation activities of the repository. The baseline database consists of a digital map that is provided by the operator of the disposal site. The database includes all buildings, roads and other constructions. It also includes optical imagery with a spatial resolution of some tens of centimeters and an accurate digital elevation model (Table II).

The optical imagery should be acquired specifically from an airborne digital imaging campaign. Stereoscopic imagery can be used to compute the digital elevation model if it is not already available earlier. Another option is to collect an accurate 3D data set through an airborne laser scanning. All data are stored in a GIS (Geographic Information System). The maps, the imagery, and the elevation model are also used to generate a three-dimensional model of the environment that can be viewed from any direction (Figure 2). The detailed model should be prepared from the repository site (i.e. the fenced area). A similar but somewhat less detailed model should be computed from the surroundings of the repository, approximately five kilometers to all directions from the repository.

In addition to the specifically collected airborne data, imagery from the same or similar instruments that are used to do the regular monitoring has to be stored into the database. This imagery (marked with sparse raster in Figure 1) has a coarser spatial resolution than the imagery

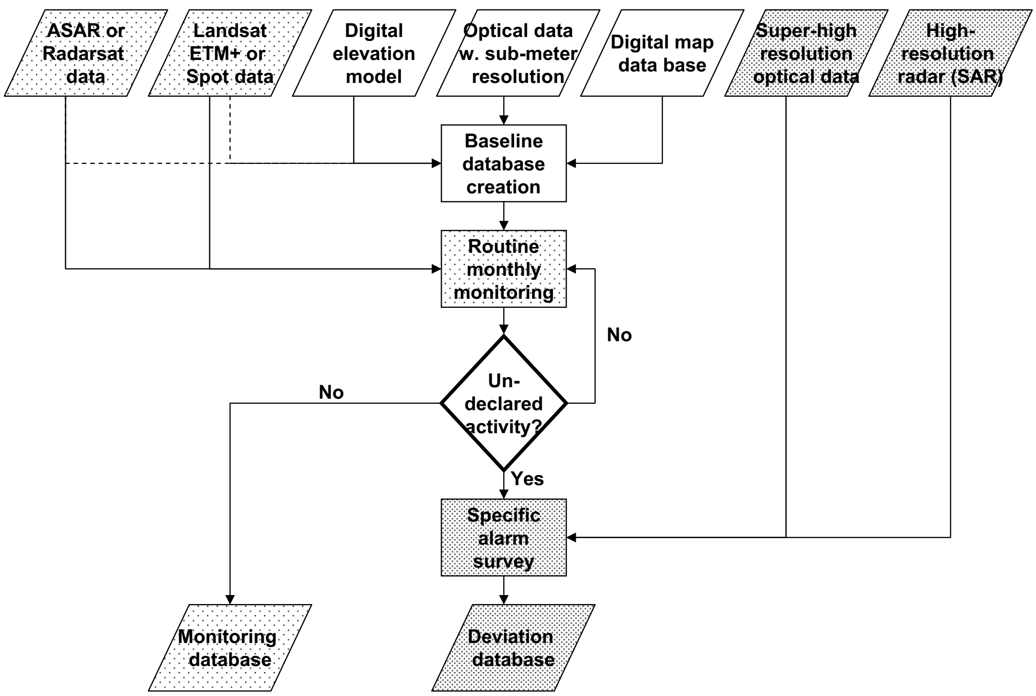

Figure 1. Phases of an earth observation based monitoring system of a repository.

Table II. Proposed earth observation and associated data from the repository for the baseline.

Data	Ground resolution (m)	Source
Repository site		
Building, road and other construction map, digital	0.2–0.4	Repository site operator
Airborne color imagery, digital	0.4	Specific imaging action
Airborne profiling scanning	0.1	Specific imaging action (optional to make a very detailed elevation model)
Elevation model, digital	0.5	From site operator or from airborne imagery
3D model with map and image data	0.5	Computed using the high-resolution data
Five-kilometer radius from the repository site edge		
Building, road and other construction map, digital	2	National Board of Survey
Elevation model, digital	2	National Board of Survey
Ikonos, QuickBird, Spot 5 or similar imagery (preferably from winter, spring, summer; 3 images in total)	1–4	Imaging ordered, purchased
Landsat ETM+, Spot HRV or similar (preferably from winter, spring, summer; 3 images in total)	10–30	Purchased
ASAR or RadarSat (radar) (from all seasons and weather conditions, 10 to 15 images in total)	10–20	Imaging ordered, purchased
3D model with map and image data	1	Computed

Figure 2. A 3D reconstruction of a village in Karelia from 1930's. http://www.vtt.fi/tte/projects/virike.

that is used to make the principal reference database. The created database is the reference with which continuously collected data are being compared.

2.2 Routine monitoring

The image for the regular monitoring includes both optical and radar (SAR – Synthetic Aperture Radar) imagery. The principal data for the monitoring has to be from radar instruments because optical imagery cannot be acquired through clouds or night time. However, optical and thermal imagery should be acquired whenever possible because exposure of bare soil, for instance, is easier to detect with optical imagery than with the available radar imagery.

The area to be monitored monthly is suggested to be the repository site and its neighborhood. The limits of the area could be approximately five kilometers from the border of the fence of the repository. It is possible to make an intensive image interpretation on the repository site and on its immediate neighborhood. In the whole monitoring area of approximately one hundred square kilometers pre-selected targets would be monitored. Detailed analysis of the whole area is not feasible because the searched change anomalies are small and at least at the beginning the analysis has to be based on manual image interpretation.

The image analysis is based on the detection of changes. The easiest way to do change detection is to overlay images from different dates and analyze change visually. Detection of changes whose area is small requires accurate geometric correction of images. Different illumination conditions cause a change effect that is similar to real changes. With radar the shadow effect can be controlled better when the images are ordered from the same orbit of the satellite. However, image acquisition always from the same direction is also a problem because important objects may be left in the radar shadow. The SAR images should preferably be acquired from two opposite directions (*i.e.* from descending and ascending orbits).

The images to be compared can be either original data or derived spectral features using the principal component transformation or similar transformation or by computing ratios of successive images, for instance. Transformations that keep the physical spectral information are more recommendable than those in which the reflected or emitted signal cannot be recovered from the transformed imagery. Therefore a straightforward use of the principal component analysis is somewhat questionable.

Automatic change analysis methods have been developed (*e.g.* Häme et al. 1998). Those methods are effective with optical data that have a spatial resolution of coarser than 10 meters. Automatic change detection methods for the radar data are in the research stage. Since the required monitoring time is very long, to the indefinite future, it is clear that the regular monitoring should be as automatic as possible. However, interactive and not fully automatic methods are proposed to start with because the present automatic methods are somewhat immature. The automatic change analysis could be done for the whole image and the most critical targets would be inspected manually.

Even though SAR images can be acquired through cloud the images are not weather-independent particularly when shorter wavelength SAR instruments are used (C band or 6 cm in ASAR and RadarSat, X band or 3 cm in TerraSAR). Particularly a wet surface changes the image considerably. Therefore the baseline data base should include images representing different environmental conditions. A new image is primarily compared with the baseline image that has been acquired during similar conditions. The proposed main phases of the interactive change analysis are:

1. Do image geometric correction and radiometric calibration;
2. Search reference image from baseline database that has been acquired during similar seasonal and weather conditions to the image to be analyzed;
3. Compute (automatically) two-temporal spectral feature that highlights change;
4. Analyze change visually;
5. If anomalies detected locate them to 3D baseline database, decide whether launch alarm procedures;
6. Store analysis results and change image to database.

2.3 Alarm survey

When the routine monitoring reveals suspicious change anomalies it can launch a specific alarm survey. For this purpose airborne techniques using either manned or unmanned aircraft would be the principal data collection tool in earth observation domain. Space-borne imaging is not the primary tool because of slow data acquisition procedure and rather low spatial resolution with presently available SAR instruments. The situation may favor more space-borne SAR imaging when RadarSat 2 data, TerraSAR data, possibly also RadarSat 3 and COSMO data with few meters resolution will become available during the latter part of this decade. Rapid acquisition of airborne remote sensing data requires also preliminarily agreed procedures with the data suppliers.

It is certain that the suspicious change anomalies are not exclusively or even primarily checked using remote sensing techniques. The anomalies should be checked against other monitoring data and inspected manually on ground.

The repetition cycle of the routine monitoring is so slow that it is possible that the alarm comes from other sources than from remote sensing data analysis. A surface anomaly can remain undetected in change analysis. In such case the alarm survey can be launched in the same manner as if the alarm were originated from the analysis of earth observation data.

2.4 Specific issues concerning Olkiluoto

Monitoring a repository that is located in northern latitudes has some specific requirements. The location of the Olkiluoto brings some own characteristics to the monitoring procedure (Figure 3, Figure 4). The very frequent cloud cover in Finland emphasizes the significance of SAR imagery, as does the long dark winter period. The seasonal changes with wintertime snow-cover are significant. The special features are taken into consideration by selecting images from different seasons and weather conditions in the baseline data set. Snow changes its spectral properties greatly in the optical and microwave spectral range when the moisture changes making image analysis more difficult. A special problem is autumn and spring when the ground is partly covered by snow. The site and its surroundings are partly forested, which restricts detection of changes on ground. Seaside location requires monitoring the sea traffic and particularly following activities in nearby islands. Despite the special features that have to be taken into consideration the proposed approach for the monitoring of the repository site should however be rather universal.

The baseline data should be collected before the excavation activities are started, i.e. in the near future.

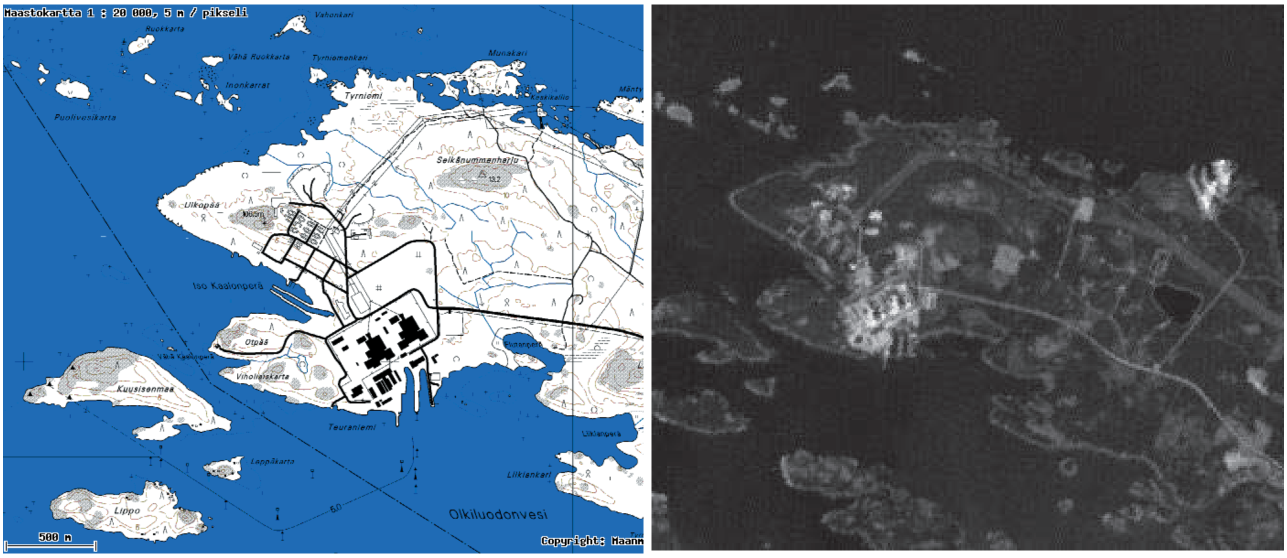

Figure 3. Olkiluoto nuclear power plant and future repository area. Left: regular map; Right: Aster satellite image August 6, 2002, red visible band, resolution 15 m.

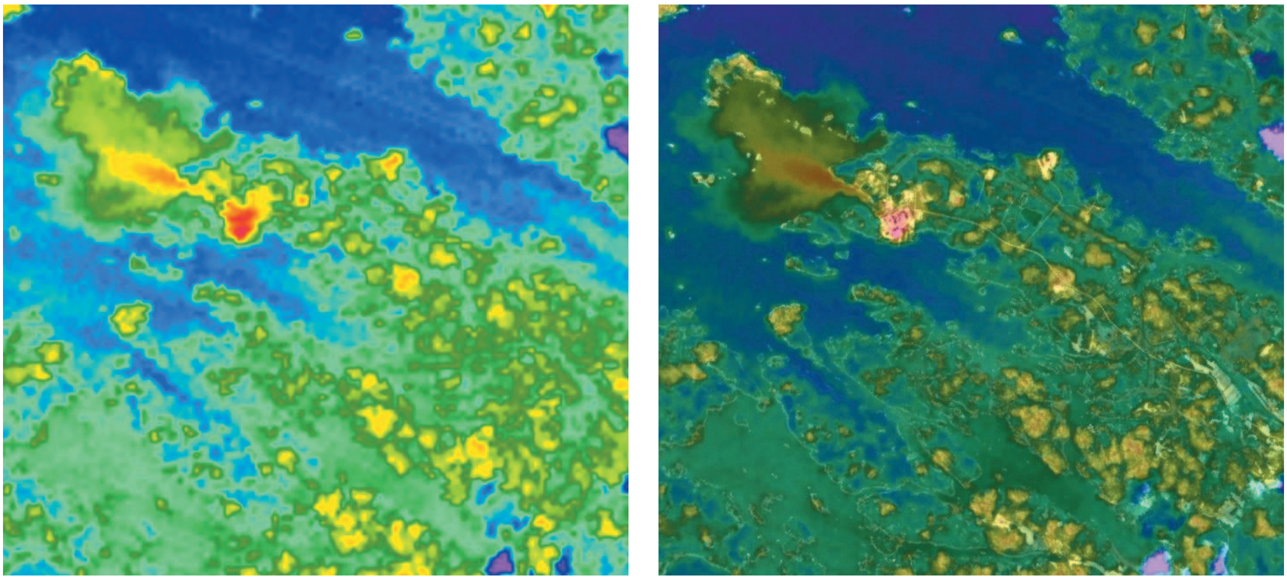

Figure 4. Left: Thermal imagery from Olkiluoto (relative rainbow scale from coolest to warmest blue, green, yellow, red); Right: Thermal imagery combined with red visible band. Aster satellite image August 6, 2002. Thermal band resolution 90 m, red band resolution 15 m.

3 Potential of remote sensing

One of the principal benefits of remote sensing data is that the site can be repeatedly documented with 100 percent area coverage. When the images are stored in a database the analyses can be redone at any moment. A large region can be monitored quickly with a standardized procedure. The proposed area to be monitored monthly is approximately 100 km^2. The observation direction from above is beneficial because the resolution of the observation is very similar at all parts of the area to be monitored and because the topographic variation normally does not prevent collecting observations.

The potential of different sensor types is hard to evaluate in a universally applicable manner. For instance, if SAR data acquisition can be optimized (the incidence angle, the frequency and spatial resolution) its potential with all listed objects in Table III can be very high. Therefore the ranking of the potential should be considered only very indicative. The spatial resolution of present and near-future non-military space-borne SAR sensors is weaker than that of the optical sensors. Also the inherent noise in SAR images, the speckle, reduces the effective resolution.

Removal of vegetation and exposure of bare soil can be detected particularly well using optical data. Thermal anomalies are certainly detectable using thermal data. The metallic objects are striking in SAR imagery. Optical data including thermal data cannot be acquired through cloud and reflected optical data requires daytime acquisition. The optical data can be collected from below clouds using a manned or unmanned aircraft if financial resources are adequate. However, because of all-weather capability the SAR is suggested as the principal imagery type in monitoring.

Earth observation instruments can not normally acquire data from below ground surface. With radar instruments information from the depth of few centimeters can be acquired. Some specific radar instruments have been developed that can reveal metallic objects and constructions

Table III. Potential* of optical, thermal and microwave remote sensing to detect some objects.

Object	Optical	Thermal	Microwave (SAR)
Building	**3** (2 to 5 depending on color, background and cover)	**3** (5 if heat emitting)	**4** (5 if metal roof; orientation affects)
Road	**4** (2 to 5 depending on color, background and cover)	**3** (2 to 5 depending on weather conditions)	**3** (2 to 4 depending on cover, material, seasonal and weather conditions)
Vehicle	**3** (2 to 5 depending on color, background and cover)	**4** (2 to 5 depending on temperature, background and cover)	**5** (3 to 5 depending on cover, orientation)
Vegetation/ non vegetation	**5**	**4** (depending on weather conditions)	**3** (depending on surface roughness)
Vegetation biomass	**5**	**4**	**4**

* From highest to lowest: 5…1 (0 would be non-existing)

from the depth of few meters. These instruments are only for airborne data acquisition. The near-future SAR instruments with few meters resolution have the high frequency X band or C band. At this frequency range vegetation effectively attenuates the back-scattered microwave signal. Thus objects that are under the forest canopy cannot be easily detected. An exception is metallic objects that are so effective scatterers that they can be detected also in the case when they are covered by trees.

With optical data only limited information can be obtained from below the canopy. However, in Finland the tree cover is usually so sparse that the canopy is not fully closed, which makes information acquisition easier. Airborne laser scanning is an option to collect accurate data from the surface. Although the canopy attenuates also the laser pulse the high resolution – some centimeters at best – of the scanning makes it possible to obtain information through small openings in the canopy. Laser scanning is presently very costly and restricted only to airborne data acquisition. Laser data can be seen as augmenting data source because it mainly gives the profile of the target but does not describe its spectral properties.

As can be seen in the tables in Annex 1, already now optical space-borne imagery with one-meter (or sub-meter) resolution are available. The highest spatial resolution of space-borne SAR instrument is presently approximately ten meters. RadarSat 2, to be launched in 2003 will have a three-meter resolution. The resolution of the TerraSAR instrument of Astrium (planned launch in 2005) is as high as one-meter at its best.

Private companies control the space-borne remote sensing instruments that have the highest spatial resolution. In practice governments have funded the development work and have a control in data acquisition. Fortunately there are several image suppliers, which reduces the risk for not getting imagery. Airborne remote sensing can be locally controlled, can provide higher spatial accuracy and is less weather dependent than the space-borne observation. Instrument operator can also modify the imagery. Therefore imagery from different suppliers and instruments is needed to minimize risk for data manipulation.

4 Costs

Rough cost estimates to establish and run the monitoring system are given in Table IV and Table V. The system is assumed to run on a regular PC that has large disk storage. The commercial software consists of a GIS (Geographic Information System) software and a database software. The image analysis software is developed specifically for the repository site monitoring application. This is the largest cost item in the system establishment. It would be possible to start monitoring work using standard image processing software and save costs in system establishment phase. However this alternative would only be applicable when the work was done by remote sensing experts. Longer-term operation will require anyway specific system development to flexibly handle the vast data storage.

The main costs to operatively run the monitoring system come from the data costs. They may be somewhat overestimated in Table V because competition will decrease prices in the future. It is assumed that one SAR image is bought every month and the optical images every second or third month. The two-day monthly work assumes that the monitoring is done interactively by an experienced image analyst. When the monitoring system is started the amount of work to do the inspection and system enhancements require significant investment. The costs during the first year after the system has been established could be one half of the building costs.

Table IV. Estimated costs to establish the monitoring system with the baseline data.

Cost item	1000 €
Hardware, software development	
• PC w. large hard disk and writable DVD	10
• Image analysis system development	200
• GIS software	6
• Database software	3
• Interface with other safeguards data	15
Baseline space-borne imagery	
• Radarsat fine beam (5 images) or ASAR	18
• Ikonos or QuickBird panchromatic (3 images)	8
• Ikonos or QuickBird multi-spectral (3 images)	8
• Landsat ETM+ (3 images)	2
Baseline airborne imagery	
• Digital aerial images	12
• Laser scanning (optional)	60
• Digital elevation model (existing)	2
Total costs	344

Table V. Estimated monthly costs to run routine monitoring.

Cost item	1000 €
Space-borne imagery	
• radarsat fine beam (1 image) or ASAR	3
• Ikonos or QuickBird panchro (0.3 images)	0.75
• Ikonos or QuickBird multispec (0.3 images)	0.75
• Landsat ETM+ (0.5 images)	0.3
Work two days	1.5
Total monthly costs	6.3
Total annual costs	75.6

5 Conclusions

Earth observation techniques can be used to monitor the repository site and its neighboring areas. The main approach is suggested to be space-borne remote sensing with SAR images because of all-weather capability. The monthly SAR image analysis is augmented using high-resolution optical data that are acquired whenever weather permits. Present SAR images have too low spatial resolution to detect and analyze small targets but this limitation should become less serious in few years, particularly after the launch of the TerraSAR. However, it is unclear, whether the distribution of SAR images with highest resolution will be somehow restricted.

The potential of earth observation was considered highest to detect undeclared construction of buildings, roads, and quarries. Vehicles can be also detected using earth observation, but real traffic monitoring would require very frequent observations, which is both impractical and costly. Ship traffic can be monitored relatively well using space-borne instruments if this is considered worth of high image costs. Space-borne remote sensing was selected as the principal earth observation method because continuous monitoring is not feasible using airborne remote sensing, either.

For the baseline airborne imagery should be acquired to assure highest possible accuracy. The baseline data should be collected before excavation activities start at the repository. Airborne campaigns could be continued at regular intervals, e.g. every second year to update the detailed reference data sets.

The proposed monitoring method is interactive image interpretation because automatic methods were not considered reliable enough. This method is not only expensive but it may have a security risk. It is very unlikely that some illegal activities could have found. When the inspection continues for years the concentration of the image analyst may weaken. Therefore research should be continued to further develop automatic change detection methods that could replace the interactive approaches. There should be always a possibility for manual image analysis. For instance it is hard to imagine an automatic image interpretation method that would reliably work springtime when partly snow-less ground has been exposed.

The earth observation monitoring system should be combined with other monitoring techniques such as the seismic monitoring.

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ANNEX 1 Selection of present and near future instruments that are relevant to the safeguards

Sensor (Satellite)	Owner	Acquisition years	Spatial resolution (m)	Spectral res. (bands)	Wavelengths (μm)		Radiometric resolution (bits)	Temporal res. (days)	Image area (kmxkm) / Swath width (km)	Cost ($/km²)
PAN (IKONOS)	Space Imaging Ltd.	1999–	1	1	0.45…0.90		11	1–3	11×11	25
MS (IKONOS)	Space Imaging Ltd.	1999–	4	4	0.45…0.53 0.52…0.61 0.77…0.88 0.64…0.72		11	1–3	11×11	18
QuickBird (QuickBird-2)	DigitalGlobe, USA	2001–	0.6/3	5	0.45…0.90	0.45…0.52 0.52…0.60 0.63…0.69 0.76…0.90	11		16.5	22
ETM+ PAN (Landsat-7)	NASA, USA	1999–	15	1	0.52…0.90		8	16	185×185	0.02…0.04
ETM+ (Landsat-7)	NASA, USA	1999–	30 60 (IR)	7	0.45…0.52 0.52…0.60 0.63…0.69	0.75…0.90 1.55…1.75 2.09…2.35 10.4…12.5	8	16	185×185	0.02…0.04
HRVIR (SPOT-4)	CNES, France	1998–	10/20	4	0.50…0.59 0.61…0.68 0.79…0.89 1.58…1.75			2–3	60×60 or 60×120	0.3…0.5
HRG (SPOT-5)	CNES, France	2002–	2.5/5/ 10/20	5	0.49…0.69 0.50…0.59 0.61…0.68	0.78…0.89 1.58…1.75		2–3	60×60 or 60×120	1…2
ASTER (Terra/ EOS AM-1)	NASA, USA	2000–	15/30/ 90	14	0.52…0.60 0.63…0.69 0.76…0.86 1.60…1.70 2.15…2.19 2.19…2.23	2.24…2.29 2.30…2.37 2.36…2.43 8.13-11.65 (4 bands)	8/8/12	2–3 (?)	60	FREE
AVNIR-2 (ALOS)	NASDA, Japan	2004	10	4	0.42…0.50 0.52…0.60 0.61…0.69 0.76…0.89		8		70	N/A

Sensor (Satellite)	Owner	Acquisition years	Spatial resolution (m)	Frequency/Band	Polarization	Operating modes	Swath width (km)
ASAR (Envisat-1)	ESA, EU	2002–	13…1000	5.3 GHz/ C-band	HH, HV, VV, VH (not fully polarimetric)	1) Image mode 2) Wave mode 3) Wide swath mode 4) Global monitor. mode 5) Alt. polariz. mode	1) 100 2) 5 3) 400 4) 400 5) 100
RadarSat 1	RadarSat	1995–	10…100	C-band	HH		
TERRASAR-X1	Astrium	2005–	1…30 (?)	10 GHz/ X-band	HH or VV	1) Spotlight 2) Stripmap 3) ScanSAR 4) Beam Steering	1) 10 2) 60 3) 200 4)
Radarsat-2	CSA/ MacDonald Dettwiler, Canada	2004–	3…100	5.4 GHz/ C-band	HH, HV, VV, VH	1) Standard/Wide Swath 2) Polarimetric 3) Fine 4) ScanSAR	1) 170 2) 25 3) 25…50 4) 530
PALSAR (ALOS)	Nasda, Japan	2004–	7…100	1.27 GHz/ C-band	HH, HV, VV, VH	1) Fine 2) ScanSAR 3) Polarimetric	1) 70 2) 350 3) 65
TERRASAR-L1	Infoterra, UK/Germany	?	1…30 (?)	1.3 GHz/ L-band	Full polarization	1) Spotlight 2) Stripmap 3) ScanSAR 4) Beam Steering	1) 10 2) 60 3) 200 4)
COSMO SkyMed	Agenzia Spatiale Italiana	2005–	1…	10 GHz/ X-band	N/A	Several	10…200

ENVIRONMENTAL SAMPLING IN MONITORING SPENT FUEL REPOSITORY

Riitta Zilliacus

VTT Processes

Contents

1 Introduction

This report describes briefly the scheme of Olkiluoto geological repository for spent nuclear fuel and provides background information of possible areas of diversion. The routes for unauthorized diversion of nuclear material are discussed. The handling and disposal of spent nuclear fuel are shortly described and opportunities for unauthorized diversion in different stage of the process are summarized.

The main purpose of this report is to describe possible methods for the detection of unauthorized diversion by using environmental monitoring of the repository. The isotopic signatures that may be present are discussed and possible analytical techniques monitoring these signatures are described. The report is based on the reports of SAGOR program.

2 Repository description

2.1 Repository concept

A repository for spent fuel in Finland will be built in Olkiluoto. The geological media will be stable, crystalline rock in the depth of 400–700 m, which can provide a long-term isolation of spent nuclear fuel from the biosphere. The research phase lasts till 2010 and the building of the repository will start after 2010. The operational phase may last up to 70–80 years starting by 2020.

The repository, according to the Posiva concept, will contain the encapsulation plant on surface with stores for spent fuel and bentonite and equipment needed for untreated water and waste water treatment [1]

The underground areas contain following rooms:

1. disposal tunnels on a single or various levels
2. access tunnels
3. shaft or/and ramp for transportation of containers
4. shaft for personnel and equipment transport
5. ventilation shaft
6. support facilities on surface and underground

The disposal rooms are arranged in panels with joint access tunnels, and containers are disposed in boreholes in the floor.

2.2 Spent fuel conditioning and characteristics

The encapsulation plant in Olkiluoto will receive and handle casks of Loviisa and Olkiluoto power plants. The casks may contain intact fuel assemblies, defective assemblies and damaged spent fuel rods. According to the Posiva concept the spent fuel is unloaded from the cask in the hot cell of the encapsulation plant. In the Loviisa cask the number of fuel assemblies is 30, each having 214 kg of fuel. The amount of fuel in a cask is 6400 kg. Castor TVO has 48 assemblies, 297 kg of fuel in each. Total amount of fuel in a cask is 14300 kg.

In the encapsulation plant the fuel assemblies are moved into the repository canisters, twelve assemblies in each. Pu content of a canister will be 14 kg in those of VVER fuel and 20 kg in BWR fuel canisters [2]. The mass of Pu in one canister is above a significant quantity (SQ) of nuclear material, the approximate quantity of nuclear material where possibility of manufacturing a nuclear explosive device cannot be excluded. For Pu SQ is 8 kg total element.

2.3 Spent fuel containers

The repository canisters of spent fuel in Olkiluoto Repository are planned to contain an inner canister of steel or iron and an outer canister made of oxygen free copper alloyed with 40–60 ppm phosphorus [1]. The inner canister is prepared by casting and the channels for the assemblies are formed casting by using a cast mould made of steel. The outer copper canister is a 50 mm thick, straight cylinder. The steel canister lid is closed with a gasket and a bolted joint. The copper canister lid is fixed by electron beam welding. Twelve fuel assemblies will be installed in one canister.

3 Possible diversion scenarios

Possible diversion scenarios are analysed in SAGOR program [3]. Potential diversions identified include diversion of a full cask, a full container, single spent fuel assemblies or rods. In this report the most likely scenario was found to be the diversion of a full cask or canister. There are several locations in the fuel handling process from which the diversion could take place. This may take place during transportation, temporary storing, conditioning or after emplacement in the repository. The easiest diversion scenarios may be above ground, but they may be difficult to conceal.

The spent fuel could be used in a clandestine reprocessing facility to manufacture a nuclear explosive device. The diversion would be concealed by falsification of records and reports, defeat in containment and surveillance, and replacement of nuclear material with dummy material. The first opportunity for diversion would be in conditioning facility where containment will be opened and there is easy access to the fuel. The on site conditioning facility make it easier to divert spent fuel, since background radiation levels would be expected to be higher than if the conditioning facility would be further away of the facility.

A similar scenario exists when the container is in the buffer storage or in the emplacement, and the emplacement room has not been sealed. This scenario would require a temporary or undeclared hot cell facility, retrieved container facility, or mobile containment vessel. If the spent fuel is reprocessed in place, volatile gas and contamination control would be needed to hide the activities.

The diversion methods may change once the container has been emplaced in the facility. The containment can be moved to the surface to an adjacent mine to have the contents removed and processed. If the material is processed in the underground facility, the plutonium would be diverted or transported to the surface with disposal of waste materials.

4 Repository monitoring

4.1 Identification of signatures

The repository will require monitoring during operation along with the inspections. The main purpose of this report is to show whether there are signatures that are detectable to indicate that diversion activity is in progress or has taken place in a repository. In a LA report from 1997, possible isotopic signatures and monitoring these are thoroughly discussed [4]. The radionuclides measurable with moderate resources are presented in Tables I–III. The pure ^{2}-emitters and nuclides decaying by electron capture or internal transition are not included in this list because of expensive and complicated analysis. Several other nuclides are also excluded if the same information is possible to obtain from a more abundant nuclide of same element, or is in the natural decay series.

The isotopes listed in Tables I–III are those present in greatest abundance or the most likely ones to escape when opening the storage cask or reprocessing spent nuclear fuel.

Table I. Suggested list of radionuclides to be measured after 20 years [4].

Radionuclide	Half life (years)
^{3}H	12.3
^{14}C	$5.7 \cdot 10^{3}$
^{60}Co	5.2
^{85}Kr	10.7
^{125}Sb	2.8
^{129}I	$1.6 \cdot 10^{7}$
^{137}Cs	30.2
^{155}Eu	4.7
^{234}U	$2.5 \cdot 10^{5}$
^{235}U	$7 \cdot 10^{8}$
^{236}U	$2.3 \cdot 10^{7}$
^{238}U	$4.5 \cdot 10^{9}$
^{237}Np, ^{233}Pa	$2.1 \cdot 10^{6}$, 27 d
^{238}Pu	87.8
^{239}Pu	$2.4 \cdot 10^{4}$
^{240}Pu	$6.6 \cdot 10^{3}$
^{241}Am	437.2

4.2 Background considerations

There are several ways of monitoring the diversion of nuclear material from a repository. Before any of these technologies may be implemented, the background concentrations of the nuclides should be considered. A reason for background concentrations of the signature nuclides is the global fallout and another one is the repository and its environment. A nuclear reactor and conditioning facility may increase the background in the area. The impact of these facilities on the background levels of radioactive signatures may be difficult to predict reliably. Therefore, the impact should be experimentally determined before the monitoring protocols are produced.

The global fallout caused by atmospheric tests of nuclear explosives are the main source of global fallout (Table IV). Same radionuclides are formed in nuclear reactors. The global fallout is a complicated mixture whose composition is influenced by the type of device tested, location of test, the mechanism of atmospheric transportation and the diffusion process coupled with various fractionation processes. Fractionation processes are possible also after deposition of thematerial on the surface of the earth. The radionuclides may also fractionate during biological uptake.

Global fallout contains many of the same radionuclides that are in the spent fuel elements to be stored in repository. It is not homogeneously deposited on the earth and may have undergone additional fractionation by geochemical or biological processes. Therefore it is necessary to charac-

Table II. Suggested list of radionuclides to be measured after 100 years [4].

Radionuclide	Half life (years)
^{3}H	12.3
^{14}C	$5.7 \cdot 10^{3}$
^{85}Kr	10.7
^{129}I	$1.6 \cdot 10^{7}$
^{137}Cs	30.2
^{234}U	$2.5 \cdot 10^{5}$
^{235}U	$7 \cdot 10^{8}$
^{236}U	$2.3 \cdot 10^{7}$
^{238}U	$4.5 \cdot 10^{9}$
^{237}Np, ^{233}Pa	$2.1 \cdot 10^{6}$, 27 d
^{238}Pu	87.8
^{239}Pu	$2.4 \cdot 10^{4}$
^{240}Pu	$6.6 \cdot 10^{3}$
^{241}Am	437.2

Table III. Suggested list of radionuclides to be measured after 1000 years [4].

Radionuclide	Half life (years)
^{14}C	$5.7 \cdot 10^{3}$
^{129}I	$1.6 \cdot 10^{7}$
^{234}U	$2.5 \cdot 10^{5}$
^{235}U	$7 \cdot 10^{8}$
^{236}U	$2.3 \cdot 10^{7}$
^{238}U	$4.5 \cdot 10^{9}$
^{237}Np, ^{233}Pa	$2.1 \cdot 10^{6}$, 27 d
^{239}Pu	$2.4 \cdot 10^{4}$
^{240}Pu	$6.6 \cdot 10^{3}$
^{241}Am	437.2

terize the global fallout in the repository area by environmental sampling before the fuel transportation to the facility will start.

The magnitude of the signatures from activities in the repository is much smaller than signatures from an operating reprocessing facility and function of activities performed at the repository. The signal from the cask opening and removing spent nuclear fuel for diversion to another location will produce much smaller signature than reprocessing the spent fuel in the repository. Also

Table IV. Global fallout radionuclides in environmental samples.

Radionuclide	Half life (years)
^{14}C	$5.7 \cdot 10^{3}$
^{36}Cl	$3 \cdot 10^{5}$
^{90}Sr	29.1
^{99}Tc	$2.1 \cdot 10^{5}$
^{129}I	$1.6 \cdot 10^{7}$
^{137}Cs	30.2
^{237}Np	$2.1 \cdot 10^{6}$
^{238}Pu	87.8
^{239}Pu	$2.4 \cdot 10^{4}$
^{240}Pu	$6.6 \cdot 10^{3}$
^{241}Pu	14.4
^{242}Pu	$3.8 \cdot 10^{6}$
^{241}Am	437.2

the technology used will affect the signature. Air emissions can be reduced by installation of HEPA filters and noble gas emissions by cryogenic scrubbing techniques. Aqueous emissions are possible to reduce by processing the effluent waters by flocculation or passing the waters through ion exchangers.

In cask opening in an underground facility ^{85}Kr is the signature that might be detectable. In facilities where damaged fuel elements are handled, background may be too high for detecting cask opening.

During reprocessing volatile radioactive gases ^{3}H, ^{14}C, ^{85}Kr are released completely and also ^{129}I will be released if it is not recovered separately. The detection of these signatures is more likely to occur than in the case of cask opening and moving the fuel to another location.

4.3 Monitoring techniques

Repository monitoring techniques are either direct measurements for prompt detection of releases that indicate diversion, or off-line monitoring where samples are collected at the repository and analysed at a laboratory. The problem with on–line monitoring is that volatile signatures may not exist. They have the advantage of fast response, but the detection limits are higher compared to laboratory techniques.

There are three volatile nuclides that may be released when a storage cask or capsule is opened for diversion or reprocessing of spent nuclear fuel and could be useful in on line monitoring of radioactivity in a repository, namely ^{3}H, ^{85}Kr and ^{129}I. These are all radioactive nuclides and may be detected by using radiation measurements. The isotopic composition of Xe could be an indicator of cask opening, but they are stable isotopes and mass spectrometric instruments are still difficult to use for on line measurements. Several important nuclides, e.g. uranium and plutonium may be released as particles to the environment. For analysing those signatures samples should be collected and analysed at a laboratory.

4.3.1 On-line measurements of volatile nuclides

There is a rather widespread variety of instruments for tritium detection. Tritium can exist in the form of tritiated hydrogen or as tritiated water. Either form of tritium present is a signature of cask opening. Gas filled detectors and scintillation detection are used for tritium detection. Background detection is important, because ^{222}Rn may increase the level of radiation underground when ionisation chamber based tritium monitors are used. The situation is the same with the low background liquid scintillation counter. With flow-through proportional counters tritium activity can be measured separately from other radioactive gases. The detection limit for tritium in air can be $< 10^{4}$Bq/m^{3} [5]. Proportional counters have also been used for ^{85}Kr detection [6]. Liquid scintillation counters are in many ways more difficult to use on-line. Tritium analysis by collecting tritium in water near the casks and analysis of samples in the laboratory may offer detection limits near background levels.

For the detection of ^{85}Kr in environmental samples several commercial detectors are available [7]. A double window pancake-type Geiger-Mqller tube had a sensitivity of 900 Bq/m^{3}. For ^{129}I detection an instrument using a sodium iodide scintillation detector has been reported [8].

4.3.2 Off-line methods

The detection limits for off-line analysis are generally lower than in on-line measurements. They are not suitable when early warning is needed, but offer a wide variety of signatures and greater reliability. Their use will be effective during the time when the repository is still open and it is possible to get underground samples. The sampling is more complicated after closing the repository as shafts and ramps will be closed.

When off-line measurements of the samples is used, the samples may be treated conventionally, and a majority of the analytical methods will be available; all radiochemical methods can now be used effectively. Electron microscopy, electron microprobe, all mass spectrometry methods and many other techniques can be used for analysis of collected samples. By a combination of liquid scintillation counting, high-resolution gamma spectrometry, alfa-spectrometry and mass-spectrometry, all important radiochemical signatures can be detected. Although analytical methods are developed, sample collection and handling are important factors in the reliability of the results. Analysis of air and soil samples near a repository for key signatures in conjunction with global fall-out data and background data has the potential to detect unauthorised diversion of spent nuclear fuel. Methodologies for in-situ repository need to be tested and sampling methods for off-line laboratory analysis need to be developed. Also, the development of new analytical methods needs to be taken into account and new instruments tested for evaluation of their capabilities for repository monitoring.

5 Conclusions and recommendations

Global fallout containing many of the radionuclides that are present in the spent fuel is limiting the capabilities to detect the signatures from unauthorised diversion of spent nuclear fuel. Fallout is not homogenous and has undergone fractionation by geochemical and biological processes. Therefore it is necessary to characterise the local situation at the repository before the first shipments of spent fuel. These background levels need to be taken into consideration in the development of Quality Control program for monitoring. A nuclear reactor near the repository may be an additional source of signature nuclides. The impact on the environment is difficult to predict.

The magnitude of the signature is a function of the activities performed in the facility. The cask opening produces a much smaller signature than reprocessing the spent fuel within the facility either one being much smaller than the signature produced by a reprocessing facility. Emissions can also be reduced when suitable techniques for cleaning the air and water releases are used.

The on-line detectors for repository monitoring need long-term testing. The stability and reliability and the incidence of false negative or positive responses are the main concerns. Sample collection methods and sample integrity maintenance are important factors in the reliability of the off line analysis of signatures.

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SEISMIC MONITORING OF ROCK EXCAVATIONS, BASELINE AT OLKILUOTO NUCLEAR WASTE REPOSITORY SITE

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Abstract

The purpose of this work is to describe and define the benefits and drawback of the geophysical monitoring methods which can be utilized in the monitoring of nuclear waste repositories. The work concentrates on seismological tools only, and does not deal with any other geophysical methods which can be taken into consideration.

The study was done by using the comprehensive seismic database of seismic events occurred in Fennoscandia and adjacent areas compiled by the Institute of Seismology. On line data from the Finnish national seismograph network station VAF is used to show the weekly and diurnal noise level variations. The station locates 200 kilometres from Olkiluoto area, and per se cannot present exactly the background noise at the repository site, but only shows the behaviour of seismic background noise, in general.

Benefits and drawbacks of the seismic methods are discussed as well as future approaches of the seismic methods.

Contents

1 Introduction

Seismic methods are efficient in different kind of monitoring tasks. They were utilized since late 1950's in monitoring underground nuclear explosions, and event before that during the World War II its chances to forecast weather in northern Europe were evaluated.

Seismological methods cover from noise studies up to the final estimation of the possible source parameters, and powers causing the phenomena. In this work the main interest is to formulate the environmental parameters which most comprehensively define the seismic characteristics of the repository site before, during and after excavation works.

In the first stage the pre-excavation temporal noise and seismic patterns are described, and as the works begin, the active period patterns are formed. These noise and seismicity patterns are then updated in the run of time to keep the "ONKALO" as intact as possible.

This paper presents the registration and analysis of data which are available from the recordings of the Finnish national seismological network, operated by the Institute of Seismology. Registrations and data are from years 2000–2001, and corresponding seismic bulletins.

2 Noise conditions

In the seismic monitoring the background noise plays a significant role. The noise can be so strong and has high amplitudes that it veils true seismic signals totally. Seismic background noise exists at all frequencies of seismic registration. Sources of long-period noise are meteorological situations over great sea areas. The behaviour of this noise is similar when registered simultaneously at sites near the coast and sites which lie far away from coastal zones.

The sources of short-period noise are natural and artificial. Artificial noise is due to traffic, industry e.g. saw mills, power plants and other hammering machinery. Also, any other human activity affects the background noise. The main sources of natural short-period noise are small sea and lake area. Also, the influence of winds against buildings, on the topography and the registration system itself, should be taken into account. Further there are noise sources which are non-seismic in nature, such as signal generated noise.

The main purpose of the noise study in this work is to show that simply monitoring the diurnal noise, and showing how the activity in the repository site can be monitored. So, any bias to normal noise pattern may lead to recovery any anomaly in the repository geology or its vicinity.

Figure 1 shows clearly the weekly noise behaviour at the Finnish national seismograph station VAF which locates at the Ylistaro municipality approximately 200 kilometres from Olkiluoto repository site. The station itself is part of the Finnish national seismic network, and is used for monitoring the seismic activity in the Bothnian Bay areas. A new seismic station will be built in Laitila in the near future, and that station is only a few tens of kilometres from Olkiluoto, and as such can be utilized to monitor Olkiluoto area and

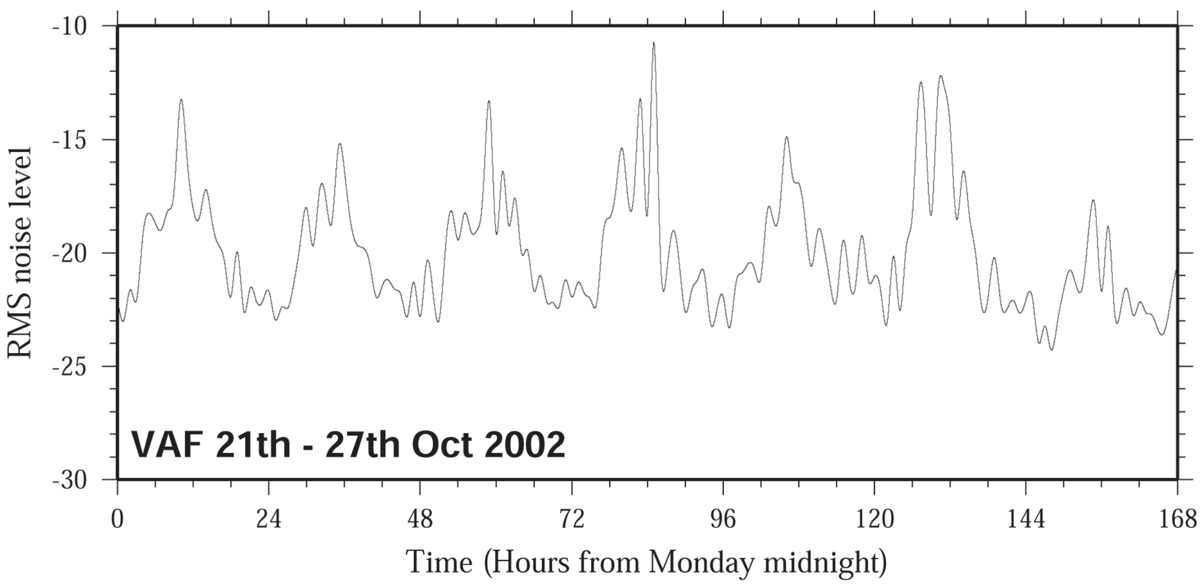

Figure 1. Virtual RMS noise level at seismograph station VAF in late October 2002. As one can see the diurnal noise level follows the human (working hours) activity in the area. The changes in the noise level are striking clear even though the station locates over 10 kilometres from a heavily used high way.

to work as a geophysical consistency monitoring tool along the microseismic array at the repository site.

The working day and free day noise levels can be seen in Figure 2 where the noise level at frequencies from 3.5 to 6.0 Hz is shown. Even the rise in the traffic can be seen during the rush hour on Monday.

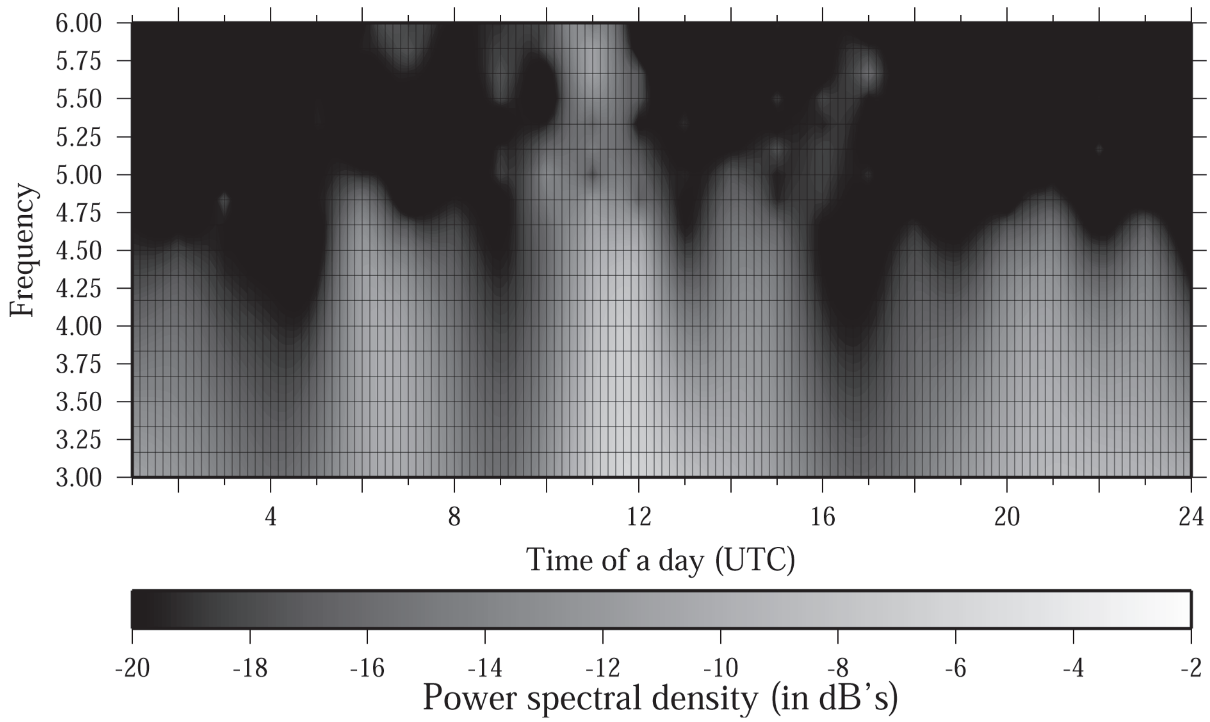

Figure 2. Noise level in dB's (rel to nm²/Hz) on Monday 21st October 3.0–6.0 Hz. The noise level rose approximately 16 dB for two hours around noon (UTC, early afternoon local time) that time of the day may present the early afternoon activity in the vicinity of the station. Without any direction estimations the source of this rise of noise level cannot be determined, but it can be connected to frequent or daily routines of agricultural works in the village nearby. Rise in the noise level in the morning at 6 o'clock and later in the afternoon around 14 can be connected to the travelling to and from jobs. Late evening and night changes in the noise level cannot be connected anything else but heavy convoy traffic to and from the town Seinäjoki.

3 Spatial seismic patterns in the area

Seismograph stations in Finland detect daily many seismic events at regional distances (Δ<2000 km). Almost all of these events stem from various kinds of explosions (Tarvainen and Husebye 1993). Such explosion recordings are of little scientific value, and add considerably the daily analyst workload. In this work the aim is to track the seismic activity near Olkiluoto repository site. The first step is to describe the seismic activity in the area. In Figure 3 there is shown the seismic events near Olkiluoto in 2000–2001. Many of the events near Olkiluoto stemmed from explosions done during construction works in the port of Rauma and two quarries in the vicinity. Some big events located at Gulf of Bothnian are due to depth charge explosions during naval training actions in the area. No earthquakes occurred in the area in 2000 and 2001 when this statistics was formed. From the point of view of monitoring the repository site the continuous seismic monitoring is essential. Any anomalies in the annual patterns must be taken into detailed examination. This does not mean only increased but also rapid changes in seismic activity, in general. The biggest problem to monitor human activity in the area is possible spoiling or veiling seismic patterns by activating some legal and announced activities near illegal access points. Anyway this kind of activities may be surveyed in many efficient ways.

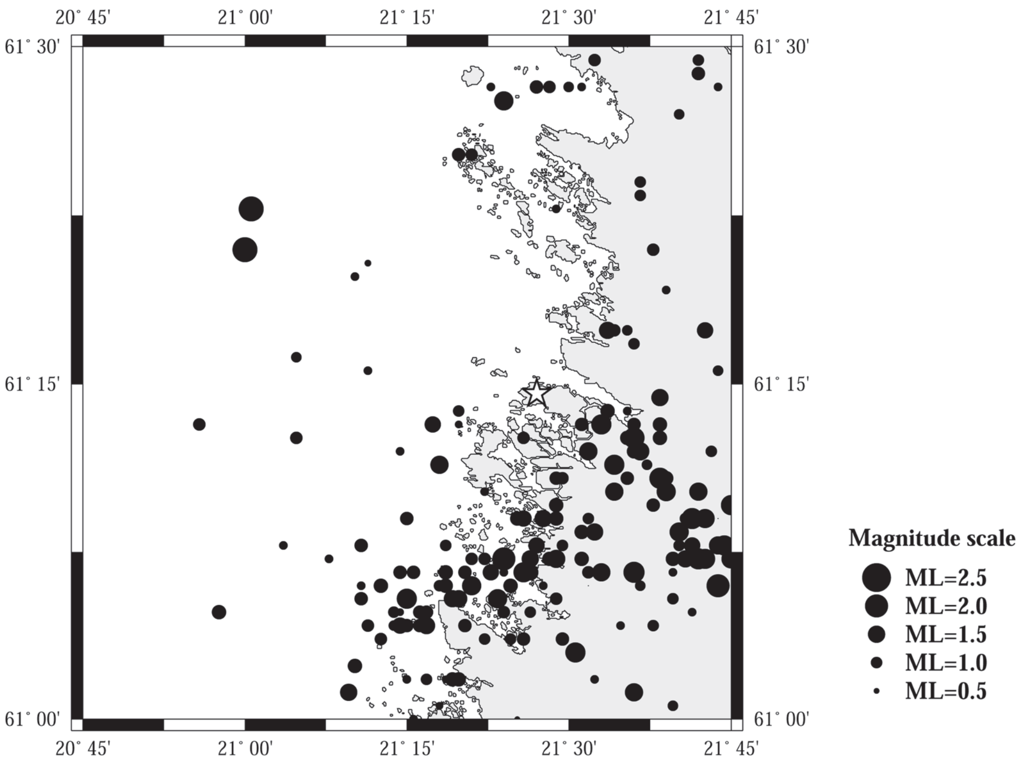

Figure 3. Seismic events in western Finland in 2000–2001. The events near Olkiluoto stem mainly from excavation works carried out in the port of Rauma and explosions in two quarries near Olkiluoto. The white asterisk shows the Olkiluoto nuclear power plant site.

4 Temporal patterns of Fennoscandian seismicity

If seismic events have clear and repeating temporal pattern, they can be assumed to have same or similar sources, such as frequently shooting mine or quarry. As most of the events daily detected by the Finnish seismograph stations stem from various mines in the area, their shooting practice should stay similar from year to year. One of the best studied mine locates in the municipality of Siilinjärvi in the central Finland. This phosphate ore mine has very distinct shooting practice. The explosions there are prominent—up to 75 metric tons of TNT equivalent—and they are practically always done 15 minutes to two P.M local time. The mine can simply be recognized from the close Nilsiä mine only 20 kilometres apart by examining the origin times of events, and also, the signal characteristics which—in Siilinjärvi case—are very strong P-phases. In Figure 4 there are shown the temporal patterns of Siilinjärvi area in 2000 and 2001. The self-organizing pattern of temporal and spatial patterns was studied by Tarvainen (2002).

The temporal pattern of events in the Olkiluoto area shows nothing else but the working day activity. All events concentrate on working days and working hours only. This can be used to

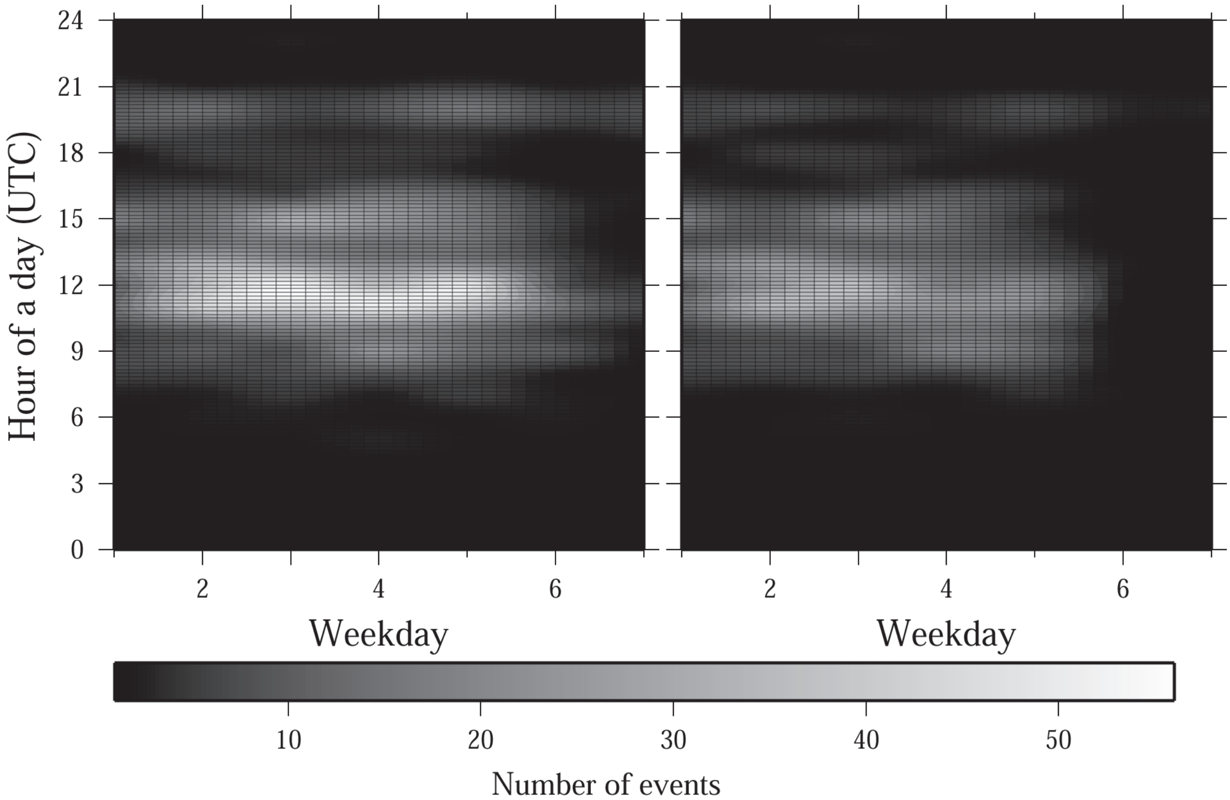

Figure 4. Diurnal and weekly distributions of origin times of events in the Siilinjärvi area in 2000 and 2001. The concentration of detections is around noon (UTC) the fact which is widely used in the source identification. Late evening events on Tuesday (day number 2) and Friday (day number 5) might have origins at road construction works in the nearby intra-national highway no. 5.

monitor well the activity in the repository site. Further, if any changes in these patterns occur they can soon be detected. In Figure 5 there is shown the weekly pattern of seismic activity in the Olkiluoto area. That activity is even more prominent and characteristic than the temporal characteristics in Siilinjärvi.

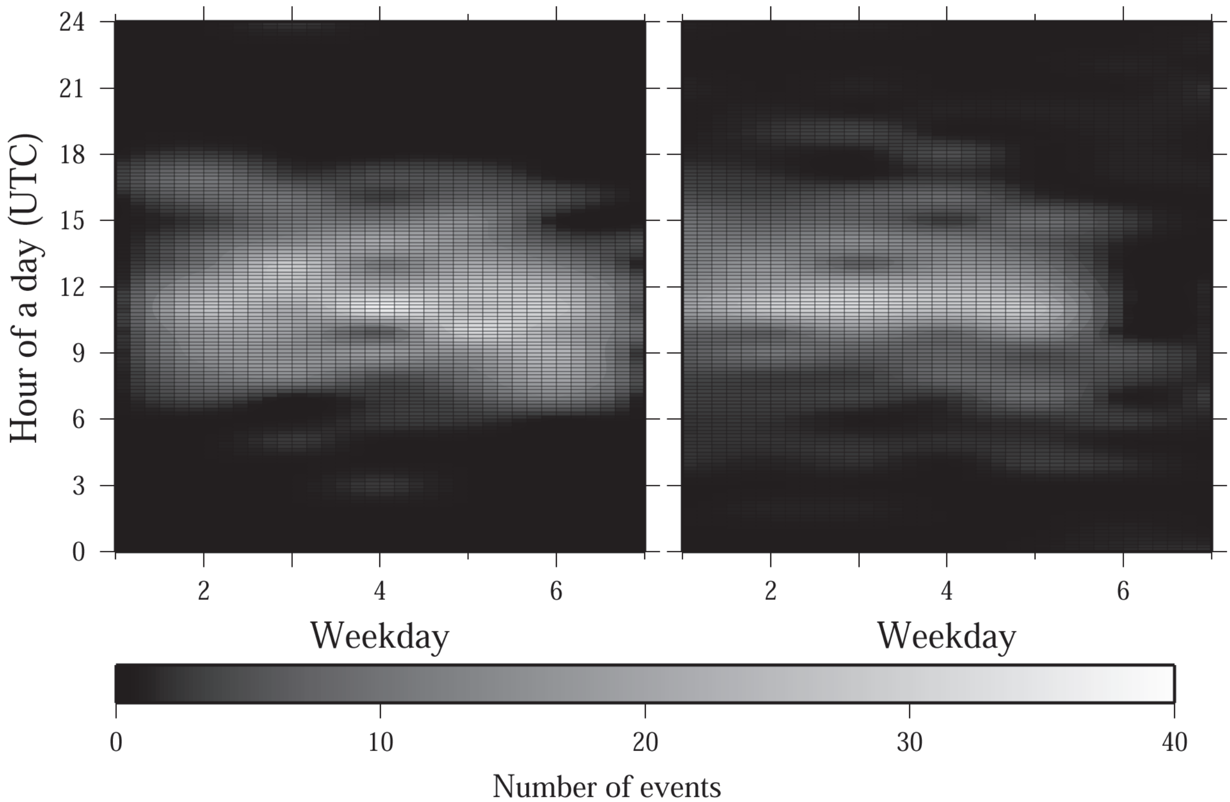

Figure 5. Daily detection activity as registered in 2000 and 2001 within 100 kilometres from the Olkiluoto repository site. Weekdays are from Monday (1) to Sunday (7). The highest activity of origin times seems to concentrate in early afternoon hours of Tuesday. Another more active time is on Thursday, also in the afternoon. White sliver-like concentrations on Saturday has no explanation.

5 Seismic risk and hazard assessment

The seismic risk in the repository area is based on the simulation of possible future earthquakes and the seismic history in the site. The seismicity in the area is dependent on several factors. One can mention the post-glacial rebound, eastward oriented ridgepush and postglacial faulting (Arvidsson 1966). The design, constructing and monitoring of the repository site requires estimation of seismic risk that earthquakes in the run of thousands of years may cause (Saari 2000). La Pointe et al. (2002) and La Pointe and Hermanson (2002) constructed scenario for the next 100000 years in which the energy release and seismic risk within 100 kilometres from the repository site are simulated. The bigger earthquakes, having local magnitudes over 5.5, can be estimated to occur in the area at the end of a simulation period. Still, these estimations are very uncertain, as the post-glacial rebound seismicity differs from the "normal" magnitude-frequency distribution.

6 Benefits and drawbacks of seismic methods in monitoring the nuclear waste repository

The seismic monitoring can be adjusted to work in the most efficient way to monitor any anomalies in the seismic patterns. Transient changes in the background noise or anomalous diurnal noise patterns may reveal activities which are zealot, illegal or hostile.

The seismic activity in the area is well monitored by the Institute of Seismology, and also some other Scandinavian authorities. Rapid or unannounced changes in the seismic activity can be considered unwanted access to the area, or some works that do not belong to the repository site surveillance nor its monitoring.

As the long-term background noise is stationary, it is easy to follow its transient changes. Yet, any illegal, activities can be tried to be veiled by activating noise sources which prevail and mimic natural sources. Anyway, modern pattern recognition methods may uncover the possible zealot access, as the best polarization analysis tools can be adjusted to certain point-like sources.

If trying to cover activities by using minor or moderate ripple fired explosions can be utilized to hide access to repository sites. Yet, this is a way which can soon be recovered.

7 Future plans

In the first phase of the monitoring tasks the seismological baseline in Olkiluoto area should be formed. This can be done by using the present microseismic array at the site. The annual and diurnal noise behaviour should be determined. Determination of seismic activity in the area can be done by utilizing the same microseismic array, or the Finnish national seismological network, and especially the new Laitila (RAF) seismograph station which will be built in 2003.

During the excavation works the seismic activity patterns are then compared with these pre-excavation results, and a standard activity period patterns are formed. In the final monitoring stage these pre- and post-excavation patterns are used to survey the activity in the repository area and in "ONKALO", as well.

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